Over-Tip Choking and Its Implications on Turbine Blade Tip Aerodynamic Performance

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At engine representative flow conditions a significant portion of flow over a high pressure turbine blade tip is transonic. In the present work, the choking flow behavior and its implications on over-tip leakage flow loss generation are computationally analyzed. An extensively developed RANS code (HYDRA) is adopted. Firstly a high speed linear cascade validation case is introduced, and the computations are compared with the experimental data to identify and establish the capability of the code in predicting the aerodynamics losses for a transonic turbine blade tip. The computational studies are then carried out for the blading configuration at different flow conditions ranging from a nearly incompressible to a nominal transonic one, enabling to establish a qualitatively consistent trend of the tip leakage losses in relation to the exit Mach number conditions. The results clearly show that the local choking sets a limiter for the over tip leakage mass flow, leading to a different leakage flow structure compared to that in a low speed and/or unchoked condition. The existence of tip choking effectively blocks the influence of the suction surface side on the over-tip flow, and hence leads to a breakdown of the pressure-driven mechanism, conventionally used in tip treatment and designs. The decoupling between blade loading and over tip leakage mass flow is clearly identified and highlighted. Furthermore, the realization of the loading-leakage flow decoupling indicates a possibility of a high-load blading design with a relatively low tip leakage loss. A high load blading is generated and analyzed to demonstrate the feasibility of such designs with a reduced tip leakage loss.

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Nomenclature

A = area

C_D = discharge coefficient

Cp = pressure coefficient

CP_0 = local total pressure loss coefficient $CP_0 = \frac{P_{oi} - P_{oe}}{0.5\rho v^2}$

$\overline{CP}_0$ = mass-averaged total pressure loss coefficient

Cx = axial chord

F = mass flux ($kg/(s.m^2)$)

κ = normalized mass flux ratio $\kappa = \frac{F_{tip} / F_{passage}}{(Cp_{ss} - Cp_{ps})/(dy/Cx)}$

OTL = Over Tip Leakage (OTL)

M = exit Mach number

P = pressure

P_{0i} = inlet total pressure

P_{0e} = exit total pressure

Re = exit Reynolds number

RANS = Reynolds-averaged Navier-Stokes (RANS)

x = axial direction

y = circumferential dimension

y+ = non-dimensional wall distance

z = spanwise dimension

ξ_{CP} = normalized local total pressure loss coefficient $\xi_{CP} = \frac{CP_0}{\overline{CP}_{0,passage}}$

$\overline{\xi}_{tip}$ = relative tip loss coefficient $\overline{\xi}_{tip} = \overline{CP}_{0tip} \Big/ \overline{CP}_{0passage}$

γ = ratio of specific heat

ρ = density

v = velocity

Subscripts

0 *total*

i *inlet*

e *exit*

ps *pressure side*

ss *suction side*

I. INTRODUCTION

A. General Background and Conventional Wisdom

For high pressure (HP) turbine stages, a major source of aerodynamic loss is the tip leakage flow in the gap between unshrouded rotor blades and the casing. Generally in the open literature, the amount of tip leakage flow has been considered to be "pressure-driven" (here the term "pressure-driven" as commonly used refers to "pressure-gradient-driven"): it is the pressure difference between the pressure surface side and suction surface side of a turbine rotor blade which drives a leakage flow through the clearance gap.

Among early flat tip studies, Booth et al. [1] showed that the over tip flow was analogous to the flow through an orifice plate, the contraction coefficient would also be similar to a sharp edge orifice. Moore and Tilton [2] reported that a vena contracta was evident after the flow accelerated into the gap, and a subsequent mixing occurred with a fairly uniform static pressure across the tip gap exit. Detailed flow structures within the tip gap were described by Heyes et al. [3], Bunker [4], and Zhou and Hodson [5]. A good summary of loss mechanisms of over tip leakage flows was given by Denton [6]. The losses related with tip leakage flow were largely separated into two parts: (i) loss that occurs inside the gap passage, (ii) the mixing loss of the leakage flow with the suction side mainstream. For the second source of losses, Denton [6] proposed a model to analyze the mixing loss of the flow ejecting from the tip gap with the mainstream. According to this model, the loss generated in the mixing between the leakage and the mainstream flow depends on the difference in the streamwise velocity between the mainstream and the leakage flow, and increases with the leakage mass flow rate.

The conventional tip designs and development of various tip loss reduction measures have been predominantly based upon the understanding described above. There are a large number of studies focusing on modeling the tip discharge coefficient for different tip geometries and flow conditions. In the early nineties, Bindon and Morphis [7] investigated the profiled tip geometry with the use of a pressure side edge radius, a suction side squealer, or a full squealer. Effects of the squealer tip on rotor heat transfer and efficiency were analyzed by Ameri et al. [8] in a numerical study. They reported no significant effect on efficiency due to the recessed tip although the over tip leakage mass flow rate is 14 percent smaller for the squealer tip as compared to flat tip. Bunker and Bailey [9] made measurements involving the addition of various tip treatments in the form of simple azimuthal and chordwise sealing strips intended to decrease tip leakage flow. Ameri [10] studied the effectiveness of the mean-camberline strip in reducing the tip leakage and the tip heat transfer as compared to a radiused edge tip and sharp edge tip. His calculations show that the sharp edge tip works best (among the cases considered) in reducing the tip leakage flow and the tip heat transfer. Camci et al. [11] carried out an experimental investigation of aerodynamic characteristics of full and partial-length squealer rims in a turbine stage. Aerodynamic performances of the suction side partial squealer and the pressure side ones were also compared. Lee and Chae [12] reported a study about the effects of squealer rim height on aerodynamic loss generation. As an alternative to the squealer, various winglet designs are employed to decrease the driving pressure gradient across the tip. Dey and Camci [13] tested different tip platform extensions (winglets) in an annular cascade to show that pressure-side extensions are highly effective in reducing the over tip leakage. Saha et al. [14] computationally investigated heat transfer and aerodynamic loss comparing different forms of winglet on flat tips and squealer tips. Harvey and Ramsden [15] showed that the winglet was a suitable alternative to a full shroud. Their calculations demonstrated that the winglet significantly reduced the over-tip leakage flow and loss. Further investigations about winglet designs have also been carried out by Harvey et al. [16] and Willer et al. [17].

B. Problem Statement and Motivation of the Present Work

The conventional wisdom of the pressure-driven leakage flow captures the basic fluid mechanic features as commonly perceived and often observed. Its usefulness is also reflected by positive outcomes of many research efforts on the tip treatment and designs (e.g. tip squealer, winglet) guided by the pressure-driven wisdom in the past. However two points are worth noting. Firstly most of these research efforts were made under low speed flow conditions, particularly on the experimental side. Secondly the effectiveness of the tip treatments seems to lack a consistent and conclusive trend, given the relatively large amount of efforts already made on the relatively small number of geometrical options. The question is, to what extent the conventional wisdom should be limited. It is suspected that the transonic nature of the flow in certain parts of the rotor tip gap might be one of possible limiters.

The knowledge that certain part of an over tip leakage flow for HP turbine blading is transonic is not new. A statement to such an effect was made more than 20 years ago by Moore and Tilton [2]: "In practice, unshrouded turbine rotor blades in gas turbines operate with transonic flow. Flow in the tip clearance gaps is then probably choked at least over part of the blade chord. The published literature appears to contain little information on tip leakage flow and heat transfer in this compressible flow regime." The shock formation due to overexpansion of a supersonic flow at the inlet to the tip clearance gap of a blade was studied by Moore et al. [18] and Moore and Elward [19] on a water table, using a sharp-edged rectangular channel. Using a two-dimensional tip gap model in a transonic flow, Chen et al.[20] observed pressure fluctuations due to the existence of shock system in their experimental and numerical studies. The choking nature of the tip leakage flow for a typical HP turbine blade with suction side Mach number near or above the sonic condition has also been pointed out by Harvey [21]. In recent years, the existence of choking and shocks within the tip gap has been identified by Green et al. [22], Molter et al. [23], and Tallman et al. [24] from one and a half stage, high pressure, transonic turbine.

Given the fundamental flow characteristics, pressure disturbances downstream of the choked region can no longer affect the flow upstream. In this case the tip leakage mass flow in the corresponding path is not a function of the suction side pressure any more. Clearly, the conventional wisdom based on the pressure difference between the two sides of the blade surfaces will no longer be valid, at least locally. The applicability of the conventional pressure driven wisdom then depends on how large the choked region would be. Hence the detailed over-tip flow field matters.

Zhang et al. [25] reported the first-of-the-kind detailed experimental evidences of the heat transfer stripe distributions caused by shock wave structures over the tip. Backed up by the experimental results, their virtual Schlieren visualizations in a CFD analysis clearly demonstrated that the stripe variations of heat flux correspond to those flow features associated with the over-tip shock system. Most recently, the over tip choking and shock structure were reported for a shroudless flat tip (Zhang et al. [26]), and even a modern winglet tip design (O'Dowd et al. [27]). Similar results have also been reported by Shyam et al. [28,29] in their numerical study for a highly loaded transonic turbine stage. Wheeler et al. [30] investigated a HP rotor blade and showed that at engine realistic Mach number the tip flow was predominantly transonic. At high speeds, the pressure side corner separation bubble reattaches through a local supersonic acceleration which halves the length of the bubble when the tip gap exit Mach number is increased from 0.1 to 1.0. In addition, shock/boundary-layer interactions within the tip gap lead to large changes in the tip boundary-layer thickness. These effects give rise to an almost opposite trend in the tip heat-transfer spatial variation along the chord compared to that of a typical blade tip in low-speed flows. O'Dowd et al. [31] measured aerodynamic losses for a transonic turbine cascade by a downstream traverse in the Oxford High Speed Linear Cascade research facility at an engine realistic Mach number and Reynolds number. The results of this experimental effort provide a good base for CFD validations for loss prediction at a transonic condition.

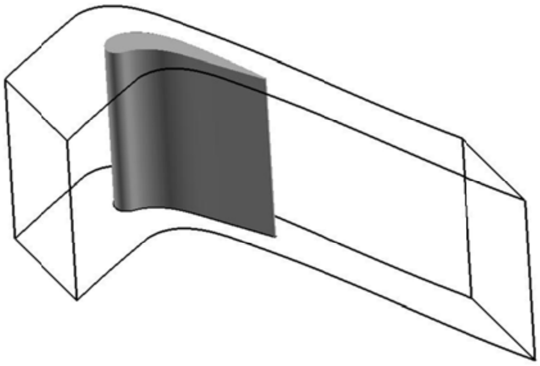
The primary issue of interest in the present work concerns the applicability of the conventional pressure-driven wisdom to transonic blade tip designs for aerodynamics loss reduction. This was raised to some extent by the qualitatively different tip heat transfer behaviors between transonic and low speed flows as recently reported, given the close link between convectional heat transfer and aerodynamics. Even from a basic viewpoint following the Reynolds analogy between the surface heat flux and shear stress, a question would be naturally prompted: what should we expect in the corresponding aerodynamic loss in a transonic tip flow if the heat transfer characteristics at such a condition are distinctively different from those at a low speed?

The present computational analysis using an extensively developed CFD code which has been recently validated for transonic blade tip configurations [25], [26], [31] should shed some light on this primary issue. Furthermore, one may ask, are there any advantageous implications if a leakage flow is made choked? A further case study is also carried out to show that there might be a feasibility of exploiting tip choking in blade designs.

II. Computational Method and Validation

The Rolls-Royce HYDRA suite was employed in the present numerical predictions. The core of the software is a preconditioned time marching solver of the Reynolds-averaged Navier-Stokes equations (RANS) [32]. The equations are discretized in space using a 2nd order edge based finite volume scheme and integrated in time using a multi-stage Runge-Kutta scheme. The time marching integration is accelerated by the multi-grid and local time stepping as standard techniques for steady flow solutions. Unsteady flow solutions can be obtained either in time domain using the dual time stepping or in a frequency domain using a harmonic formulation. In the present work, steady RANS calculations are performed and the standard Spalart-Allmaras (SA) turbulence model [33] was implemented. The conventional boundary conditions for turbomachinery flow calculations are used. The stagnation pressure, stagnation temperature and flow angle are specified at inlet, and the static pressure at exit.

Figure 1 presents the computational domain and mesh employed in the present study. The computational domain consists of one single blade with periodic boundary conditions. The same blade definition was employed by O'Dowd et al [31]). The tip gap clearance is equivalent to 1% of the rotor span.



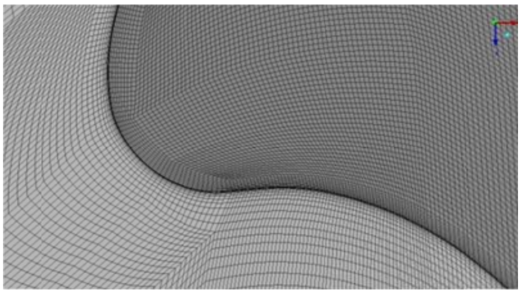


Fig. 1 Computational domain and mesh employed in the present study.

The ICEM code [34] is used for mesh generation. The mesh features 6.5 million hexahedral cells with 70 grid lines in the tip gap. Y^+ values at the first cell from the surface are kept approximately 1-2. No "wall function" is employed in the present study. All solutions presented are also grid-independent (reported by O'Dowd et al [31]), which is verified by observing negligible changes to predicted quantities as the grid density (near wall grid size/expansion ratio) is changed. The aerodynamic loss values are no longer changed while further reducing the near wall grid size.

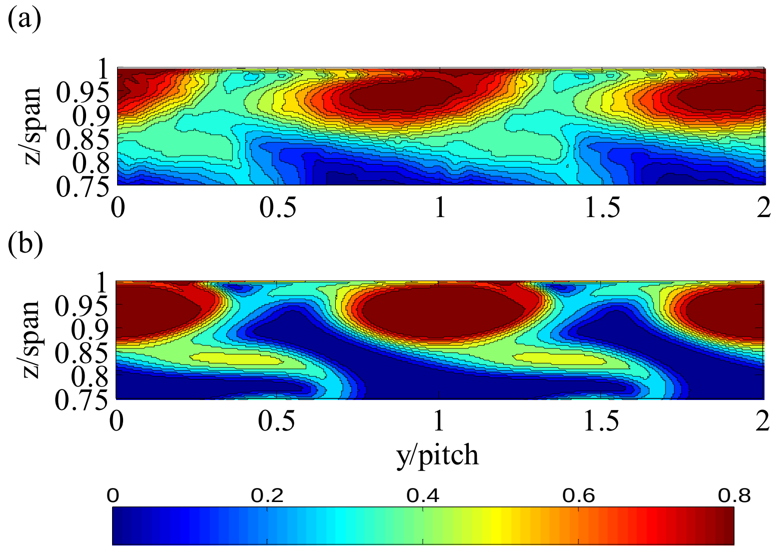


Fig. 2 Loss coefficient CP_0, one blade chord downstream, (a) experimental data (O'Dowd et al. [31]), (b) HYDRA result.

For the purpose of the code validation, the same inlet and exit flow conditions measured from previous experimental study by O'Dowd et al. [31] are employed in the present numerical work.

The local total pressure loss coefficient CP_0 is defined using the equation given by

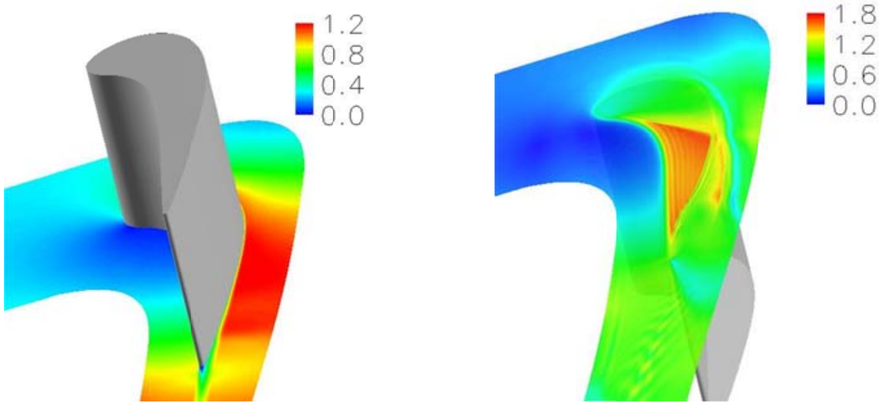
$$CP_0 = \frac{P_{oi} - P_{oe}}{0.5\rho v^2} \quad (1)$$

Figure 2a presents loss coefficient CP_0 distribution measured one axial chord downstream of the blade in the experiments of O'Dowd et al. [31]. HYDRA numerical predictions give overall good agreement, as shown in Fig 2b. Generally, the sizes and magnitudes of the over tip leakage loss core are similar in both Fig. 2a and 2b.

It is worth noting that the trend of tip heat transfer has also been well predicted by the HYDRA code, as reported by Zhang et al. [25]. Overall the HYDRA's predictive capability for transonic tip heat transfer and aerodynamics as illustrated here and in other recent studies is satisfactory and gives sufficient confidence in using the solver for computational studies.

III. Analysis of Over-Tip Choking and Its Implications

Firstly the basic flow patterns are examined for this nominal transonic flow conditions (1% tip gap). In particular, the flow within the tip gap is compared with that of the main blade passage. Figure 3 shows the isentropic Mach number contours along two different cut planes of the flow passage. The middle-span passage Mach number contours are presented in Figure 3a. The suction surface side of the main passage flow is transonic and the peak Mach number is about 1.2. The Mach number distribution is consistent with the operating condition of a typical HP turbine rotor blade. Figure 3b gives the Mach number contours along a cut plane in the middle of the tip gap. It can be observed that a large portion of the blade tip (over 60 percent) experiences a transonic flow, and the peak Mach number reaches 1.8. Hence a significant part of the tip is choked. It is also useful to note that the different flow patterns and Mach number distributions between the two parts would mean that that the main passage and the tip do not become choked at the same time. Numerical tests for the same blading at different velocity conditions show that the tip becomes choked first, consistent with the higher peak Mach number in the tip region as shown in Fig.3b.



(a) **(b)**

Fig. 3 Local Mach number contours along cut planes of (a) mid-span, and (b) middle tip gap.

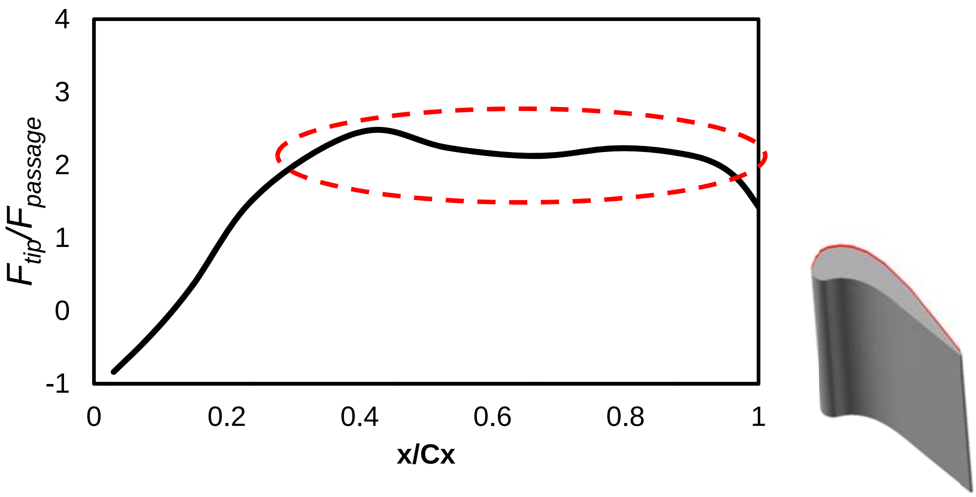


Fig. 4 tip leakage flow mass flux ratio $F_{tip} / F_{passage}$ **along the axial chord**

Now the local tip leakage flow distribution along the blade chord is examined. Figure 4 presents the tip leakage mass flux ratio (the leakage mass flow per unit area, normalized by that for the main passage, $F_{tip} / F_{passage}$ distribution along the axial chord direction. It is obtained by integrating the mass flow across the mesh surface at the exit of the tip gap along the suction side edge of the tip surface. It can be seen that over the rear part of the tip surface (from *x/Cx* = 0.5 to 1), the tip leakage mass flux ratio stays largely constant. This corresponds to the supersonic region shown in Fig. 3b. Clearly, a limiter on the leakage flow is set for the tip leakage flow mass flux once the flow is locally choked.

For an ideal compressible fluid, the choking mass flow rate is solely determined by the upstream flow capacity, and in this case, it is that on the pressure surface side:

$$\dot{m} = C_D A \left(\frac{P_0}{\sqrt{T_0}} \right)_{PS} \sqrt{\frac{\gamma}{R}} \left(\frac{\gamma+1}{2} \right)^{-\frac{\gamma+1}{2(\gamma-1)}} \qquad (2)$$

In addition to the effective throat area within a fixed tip gap, it is only the pressure surface side total pressure and total temperature which determine the tip leakage mass flow. The over tip leakage flow mass flux is no longer determined by the pressure difference across the blade tip for a large portion of the tip surface, which is in contrast to the "pressure-driven" conventional wisdom as introduced earlier.

Compared with an un-choked over tip leakage flow at a low speed condition, the over tip choking would be expected to bring about different flow patterns with corresponding loss generation mechanisms within the tip gap. For a comparison purpose, two calculations at lower flow speeds were carried out for the same configuration. The Reynolds numbers are kept largely the same by scaling the blade profile, only the exit Mach number is varied. It must be recognized that a quantitative comparison for a given tip configuration is virtually impossible. As the flow velocity changes, the effect of the compressibility would change (even without a shock wave), hence a detailed re-profiling will have to be had to match the non-dimensional load distribution. Due to the different tip geometry (blade thickness in particular), a re-profiled blading matching the loading (non-dimensional pressure difference) will inevitably mismatch the tip pressure gradient and hence the OTL flow. Therefore the comparison in the OTL performance among different flow conditions can only be regarded as qualitative, and the option of using the same blading without reprofiling is taken here for its simplicity. Table 1 gives the detail conditions for all three cases discussed next.

Table 1. Flow conditions for three exit Mach numbers

M	1.01	0.54	0.37
Re	1201546	1199029	1198356
Scaling factor	1.000	1.225	1.588

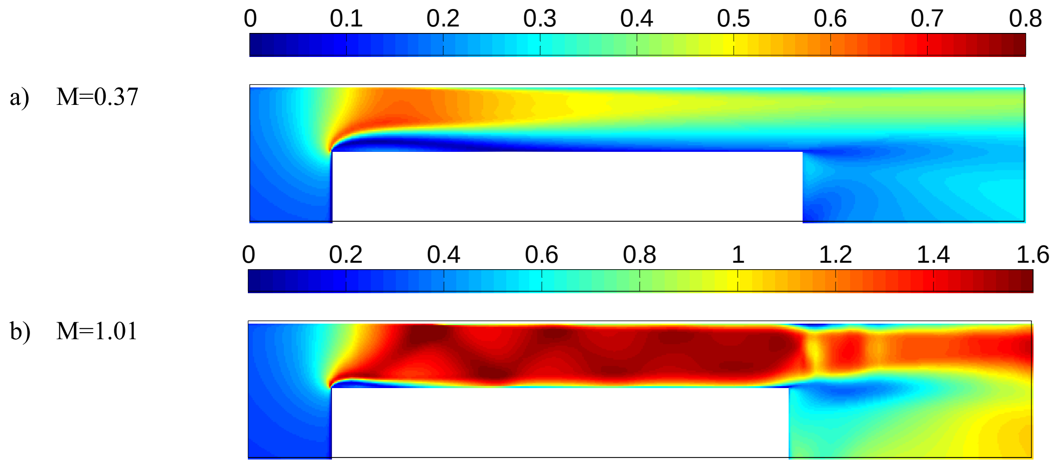


Fig. 5 Mach number contours along an axial cut plane (at *x/Cx*~0.7) for subsonic and transonic tip flow. a) M = 0.37, b) M = 1.01.

Figure 5 presents Mach number contours on a cut plane normal to the axial direction (around the rear part of the tip surface, *x/Cx=0.7*) for a low subsonic and a transonic tip flow. At an exit Mach number of 0.37, Fig. 5a shows a typical over tip leakage flow pattern similar to those presented in many open literatures for low speed tip flows. Driven by the pressure difference between the pressure side static pressure and the tip gap exit static pressure on the suction surface side, the tip leakage flow accelerates, separates, and then mixes out at the tip gap exit. Fig. 5b shows a qualitatively different flow feature at an exit Mach number of 1.01. These transonic flow features include a dramatic reduction in the size of the separation bubble, reflections of oblique shocks between casing and tip, thinning and thickening of the tip boundary layer, a normal shock at the tip gap exit, etc. The effective throat area for OTL flow decreases significantly as the separation bubble shrinks. A similar comparison for another HP rotor blade was presented by Wheeler et al. [30] in their numerical study. In the experimental study of Zhang et al. [25], the impact of shock reflection mechanism on tip heat transfer was observed from their infrared thermography measurements.

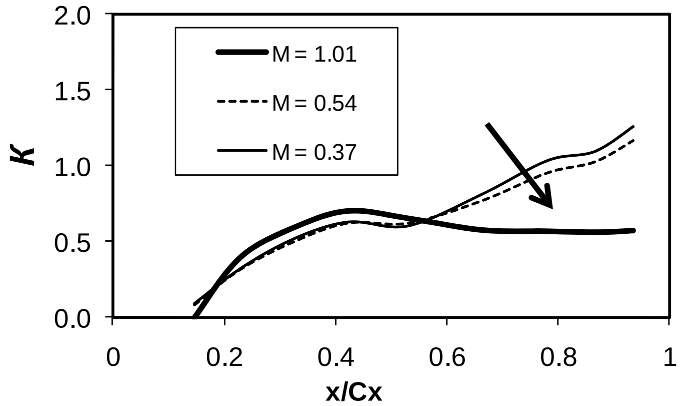


Fig. 6 Distributions of "Pressure-driven mass flux" κ along axial chord for three exit Mach numbers.

As introduced earlier, the primary objective of the present work is to examine the applicability of the 'pressure driven' mechanism. More specifically, to what an extent can the over-tip leakage flow be directly linked to the local blade loading? To address this, the local leakage mass flow normalized by the over-tip pressure gradient should be examined. A parameter to serve such a purpose is defined as a non-dimensional "pressure-driven mass flux",

$$\kappa = \frac{F_{tip} / F_{passage}}{(Cp_{ss} - Cp_{ps})/(dy/Cx)} \qquad (3)$$

where dy is the local blade tangential thickness and hence $(Cp_{ss} - Cp_{ps})/(dy/Cx)$ is approximately the non-dimensional local pressure gradient in the tangential direction..

Figure 6 presents the normalized 'pressure-driven mass flux' κ along the axial chord for three exit Mach numbers investigated. For the pressure driven mechanism to dominate the tip leakage flow, the distribution of κ should be independent of Mach numbers. For the first half of the tip, the normalized mass flux ratios are largely independent of exit Mach numbers. This is as expected because, for all three cases investigated, the flow within the frontal region is subsonic and should be driven by the pressure gradient across the tip surface. Similarly, for the two subsonic cases (M = 0.37 and 0.54), κ curves are also largely overlapping for the rear half of the blade. The good agreement among the three cases for the frontal half of the blade is quite remarkable, justifying the approach taken here to compare the OTL flow at different velocities for the same blading, recognizing that the detailed blade loading distributions for these three cases are different due to the compressibility effect as discussed above.

On the applicability of the pressure-driven mechanism, a given pressure gradient in the rear part of blade with choked tip flow certainly appears to produce a far less leakage mass flow at the transonic flow condition than in its subsonic counterparts, as shown Fig. 6. The clear departure of the 'pressure-driven mass flux' curve at M=1.01 from those of the other two subsonic cases confirms the break-down of the conventional "pressure-driven" wisdom for the tip leakage flow for choked flow. Again, the mass flow limiter due to choking manifests itself consistently in the markedly reduced local leakage flow in the rear part of the blade.

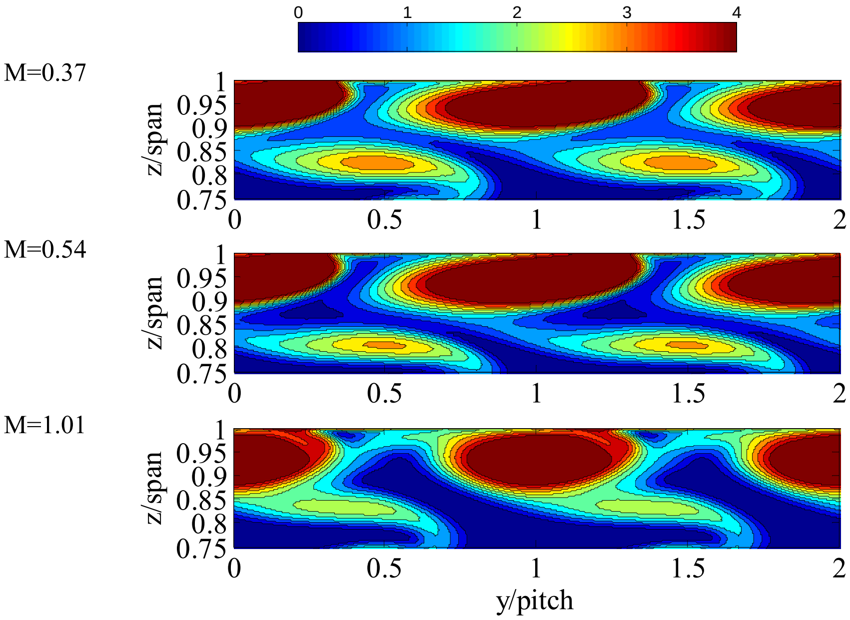


Fig. 7 Normalized local total pressure losses coefficient ξ_{CP} for different exit Mach numbers.

Having identified the distinctive leakage-flow pattern under the influence of the choking limiter at a transonic flow condition, we now look at its implications on the loss generation. In general at a transonic condition, blade profile loss is expected to increase. It is thus informative to see how the local loss near tip varies relatively to the total loss though the whole blade passage. Here, a normalized local stagnation pressure loss coefficient ξ_{CP} is defined as,

$$\xi_{CP} = \frac{CP_0}{\overline{CP}_{0\,passage}} \qquad (4)$$

where CP_0 is the local total pressure loss normalized by the exit dynamic head, $\overline{CP}_{0\,passage}$ is the overall mass-averaged total pressure loss for the whole passage.

Figure 7 presents the normalized total pressure loss coefficient ξ_{CP} contours for all three exit Mach numbers investigated. For the two subsonic flow cases (M=0.37 and M=0.54), the sizes of the tip leakage loss cores are quite similar, so are the magnitudes and the distributions of the losses. For the transonic tip flow however, the tip leakage loss core is apparently smaller and the relative tip leakage loss is lower.

To compare the aerodynamic performances more closely, the total aerodynamic loss is broken down into two parts, one due to the tip leakage and the other due to others sources. For each case, an extra calculation was carried out with a zero tip gap. The tip leakage loss coefficient is taken to be the difference between the overall mass-averaged blade passage loss with the tip gap ($\overline{CP}_{0passage}$) and that without tip gap ($\overline{CP}_{0passage\_withoutgap}$) (remove the comma, change accordingly)

$$\overline{CP}_{0tip} = \overline{CP}_{0passage} - \overline{CP}_{0passage\_withoutgap} \qquad (5)$$

Table 2 presents breakdown values of each loss coefficient ($\overline{CP}_{0passage}$, $\overline{CP}_{0passage\_withoutgap}$, and $\overline{CP}_{0tip}$). As the blade Mach number (hence loading) increases, the results show increases of both the profile and secondary flow loss ($\overline{CP}_{0passage\_withoutgap}$) and the overall loss ($\overline{CP}_{0passage}$) as expected. An interesting and important note is that the rate of increase in the profile and secondary flow losses with the Mach number outpaces that for the tip losses. Consequently there is a noticeable reduction of the relative tip leakage loss at the transonic condition. Table 2 illustrates this feature very clearly in terms of $\bar{\xi}_{tip}$ which is the tip loss relative to the overall loss, $\overline{CP}_{0tip} / \overline{CP}_{0passage}$. Although we should be cautionary here in relation to the absolute values in the aerodynamic loss predicted, the results in their relative values do nevertheless suggest a clear trend that the tip leakage loss in relation to the overall losses does seem to decrease with an increase in Mach number. This also seems to be in line with what we might qualitatively expect from the influence of the choking flow limiter.

Table 2. Aerodynamic Losses for Three Exit Mach Numbers

$\mathbf{M_2}$	0.37	0.54	1.01
$\overline{CP}_{0passage}$	0.1452	0.1488	0.1898
$\overline{CP}_{0passage\_withoutgap}$	0.0768	0.0776	0.1133
$\overline{CP}_{0tip}$	0.0684	0.0712	0.0765
$\bar{\xi}_{tip}$ ($\overline{CP}_{0tip} / \overline{CP}_{0passage}$)	0.471	0.478	0.403

IV. High-Load Blading Design with Relatively Low Tip Leakage Loss

A common challenging task for a higher load blading design is to minimize the higher loss typically associated. For over-tip leakage losses in HP turbine blades, the tip choking seems to imply an interesting perspective. If the HP rotor tip has to be partially choked in reality, the designer should take the choking flow feature into account when considering the tip leakage loss during blading design. Looking at this differently, it might even be possible to take advantage of such a special flow phenomenon. The decoupling between blade loading and tip leakage flow for a transonic tip points to a potential to design an extra highly loaded blade without proportionally paying additional over tip leakage loss penalty (as a limiter is set for the tip leakage mass flow). In that context, two options are envisaged:

a) For the part of the blade where the tip is already choked, increase the local loading without increase in tip leakage loss.

b) Load up the unchoked part to choke it, leading to a large increase in the load leading with relatively small increase in tip-leakage loss.

Both options can also be used simply as a tip leakage loss limiter, so that for high load blading, the main focus for the designer is to control the profile and secondary flow losses. Option a) would need detailed blade profile changes to achieve a local load increase. Option b) can be achieved more simply by an overall load increase.

Figure 8 illustrates a simple way to increase the overall blade loading by reducing blade count (increasing blade pitch). The nominal blading design is the same as that used in the computational analysis presented in the last section. For the high load design, the blade pitch is increased by 10 %. Figure 9 presents the blade loading distributions for a normal pitch case and a 110% pitch case. Approximately, enlarging the blade pitch by 10 % results in about 15 % increase in the overall integrated blade loading.

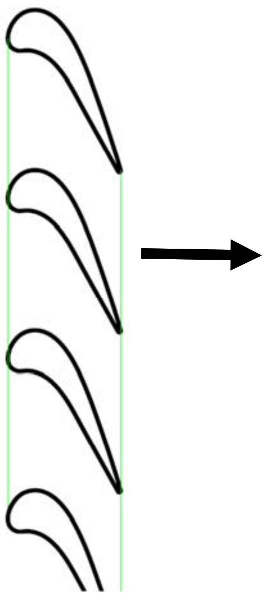


Fig. 8 A high load design: increase of blade pitch by 10 percent.

(the dashed lines indicate the original blading positions).

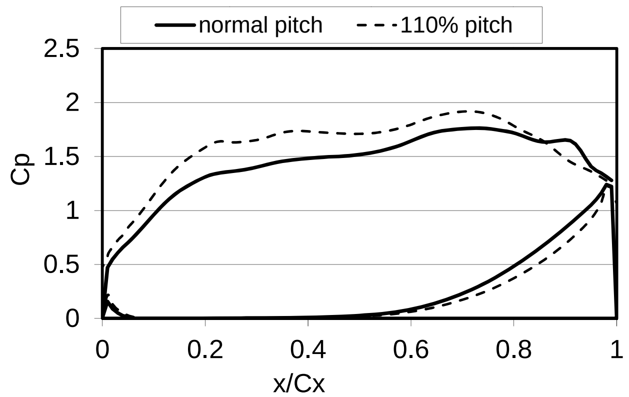


Fig. 9 Comparisons of blade mid-span loading (nominal pitch versus 10 percent increase of pitch).

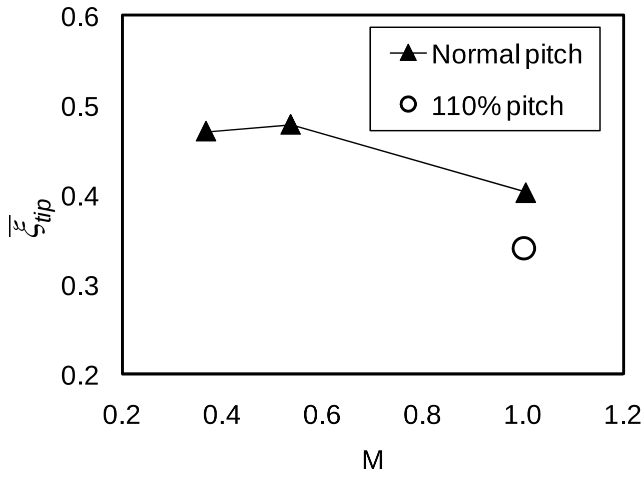


Fig. 10 Relative tip loss coefficient $\overline{\xi}_{tip}$ at different exit Mach numbers.

Table 3. Aerodynamic Losses for Nominal and High-load Blading

Blade pitch	100% (nominal)	110% (high load)
M	1.01	1.01
$\overline{CP}_{0passage}$	0.1898	0.1986
$\overline{CP}_{0passage\_withoutgap}$	0.1133	0.1310
$\overline{CP}_{0tip}$	0.0765	**0.0676**

Figure 10 presents the relative tip leakage loss coefficient $\overline{\xi}_{tip}$. For the nominal blading, the tip leakage loss at exit Mach number of 1.01 is relatively lower compared with the two subsonic cases. This is consistent with the contour plots presented in Fig. 7. At the transonic flow conditions, the high load design shows interestingly a much lower relative tip leakage loss than that of the nominal. Table 3 presents the breakdown values of each loss coefficient ($\overline{CP}_{0passage}$, $\overline{CP}_{0passage\_withoutgap}$ and $\overline{CP}_{0tip}$) for these two designs. As the blade loading increases, both the profile and secondary flow losses ($\overline{CP}_{0passage\_withoutgap}$) and the overall loss $\overline{CP}_{0passage}$ increase. Now, the increase in the profile and secondary flow losses seems to outpace that of the overall losses. And consequently, there seems to be even a slight reduction in the tip leakage loss $\overline{CP}_{0tip}$ for a high load design (Table 3). Again with a cautionary note on the absolute loss values predicted, the attention should be paid to the qualitatively consistent trend, indicating the potential in controlling tip leakage losses by taking the advantage of the decoupling between loading and leakage flow.

At this point it should be commented that there might be some other beneficial aspects of a high-loading blading design. On the heat transfer side, the heat transfer coefficient was much lower within the transonic tip region than the subsonic region due to the low turbulence diffusion, as reported by Zhang et al. [25, 26]. A fully choked rotor tip would then have less cooling requirement due to the heat load reduction. Other advantages of a highly loaded blade include lower manufacturing costs and weight for reduced blade numbers. Also, a smaller blade count means less cooling flow required.

Finally it is recognized that all the analyses presented so far are confined to a cascade configuration with a stationary casing. Some preliminary evaluations of the influence of a moving casing have been reported by Zhang et al. [26], O'Dowd et al [31] for the same and similar transonic blade tip configurations. Their results suggest that while a moving wall can reduce the size of the transonic region, a significant part of tip (over 40 percent) still remains transonic. There have been also other detailed experimental data and CFD analysis results with the moving casing showing a transonic nature of the over-tip flows, e.g. Green et al. [22], Molter et al. [23], and Tallman et al. [24].

V. Conclusions

This paper presents a computational analysis on the HP turbine blade over tip leakage flow at a transonic condition. A particular focus is on the over-tip flow choking behavior and its important implications on loss generation mechanisms. The main conclusions are,

1) A large portion of the flow within the tip gap can be transonic in an engine realistic condition, leading to qualitatively different over tip flow structures compared to those in a low speed.

2) The local flow choking within a tip gap sets a limiter on the local over tip leakage flow rate. The decoupling between the blade loading and the over tip leakage mass flow is clearly illustrated. The existence of a choked tip flow effectively blocks the influence of the suction surface side on the over-tip flow, and hence leads to a breakdown of the pressure-driven mechanism, conventionally used in tip treatment and designs.

3) The present computational analysis indicates a clear qualitative trend that the tip leakage loss is proportionally reduced in relation to the overall loss as the blade Mach number increases.

4) The feasibility of a highly loaded blade with minimal or no additional over-tip leakage loss penalty is explored. The results of a preliminary case study for a high load design alternative indicate a positive prospect of such an approach.

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